

State of Jet Noise Prediction—NASA Perspective

Presented by: James Bridges

Abstract:

This presentation covers work primarily done under the Airport Noise Technical Challenge portion of the Supersonics Project in the Fundamental Aeronautics Program. To provide motivation and context, the presentation starts with a brief overview of the Airport Noise Technical Challenge. It then covers the state of NASA's jet noise prediction tools in empirical, RANS-based, and time-resolved categories. The empirical tools, requires seconds to provide a prediction of noise spectral directivity with an accuracy of a few dB, but only for axisymmetric configurations. The RANS-based tools are able to discern the impact of three-dimensional features, but are currently deficient in predicting noise from heated jets and jets with high speed and require hours to produce their prediction. The time-resolved codes are capable of predicting resonances and other time-dependent phenomena, but are very immature, requiring months to deliver predictions without unknown accuracies and dependabilities. In toto, however, when one considers the progress being made it appears that aeroacoustic prediction tools are soon to approach the level of sophistication and accuracy of aerodynamic engineering tools.



State of Jet Noise Prediction—NASA Perspective

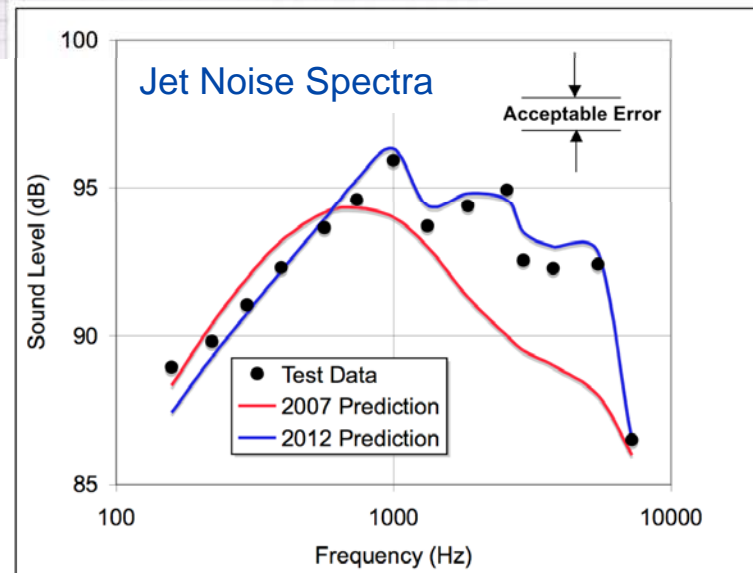
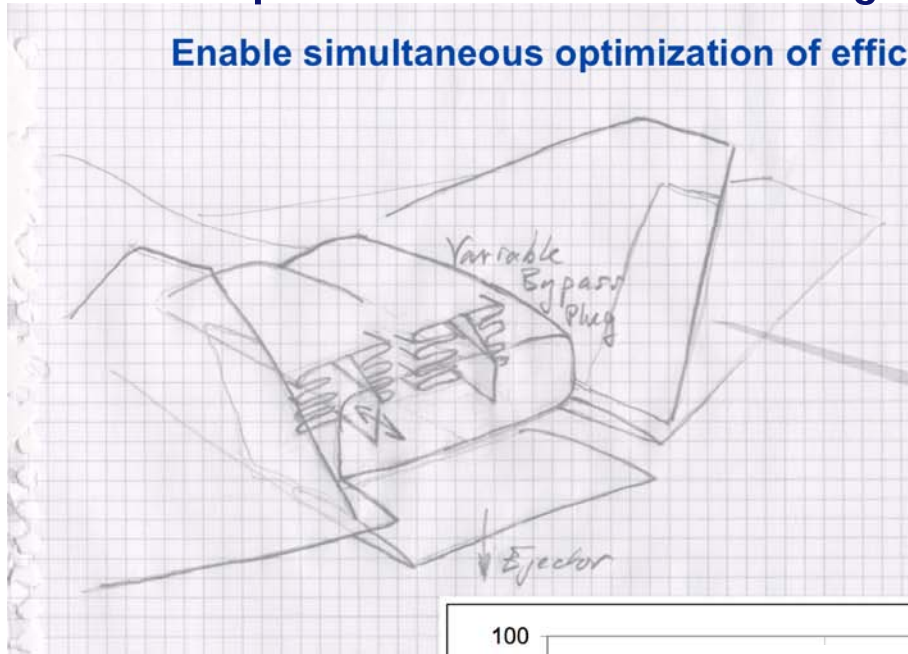
Fundamental Aeronautics Program Annual Meeting
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Contributors: Abbas Khavaran, Stewart Leib, Marvin Goldstein, Jim DeBonis, Sanjiva Lele,
Philip Morris, Dan Bodony, Amy Mielke, James Bridges



Airport Noise Technical Challenge

Enable simultaneous optimization of efficiency, emissions, AND noise.





Airport Noise Elements

- **Prediction**
 - Time-resolved CFD/CAA for Jet Aeroacoustics
 - RANS-based Modeling of Supersonic Jet Noise
 - MDOE-based Empirical Prediction Tool for ANOPP
 - Assessment of Supersonic Noise Prediction Tools
- **Diagnostics**
 - Turbulence Statistics for Statistical Noise Prediction
 - Supersonic Aeroacoustic DB for Dual Flow Jets
 - Phased Array Survey of Broadband Shock Noise Source
- **Engineering**
 - Shock Modifications for Noise Reduction (N+1)
 - Offset Stream Concepts (N+1)
 - Highly Variable Cycle (HVC) Concept (N+1)
 - SERDP Hi-Perf Noise Reduction (N+1)
 - Iconic Supersonic Vehicle (N+2)
 - Unsteady Actuator Validation (N+3)

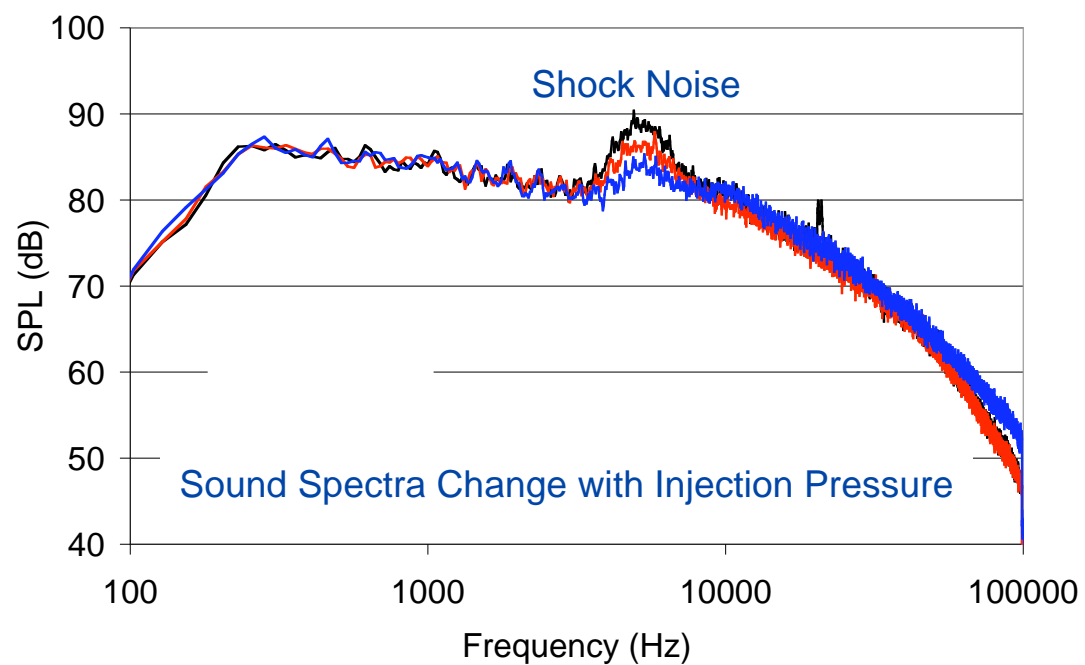
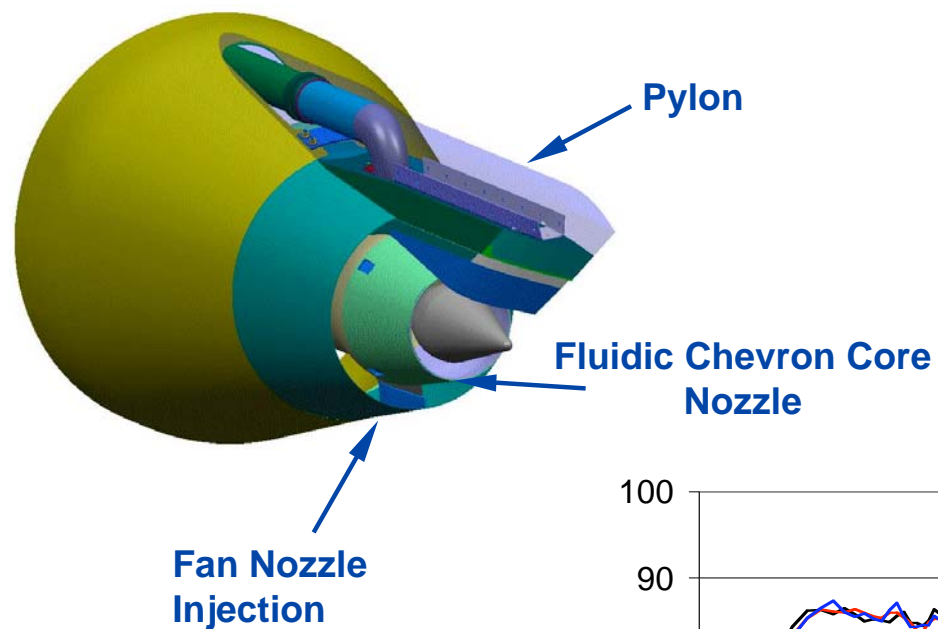


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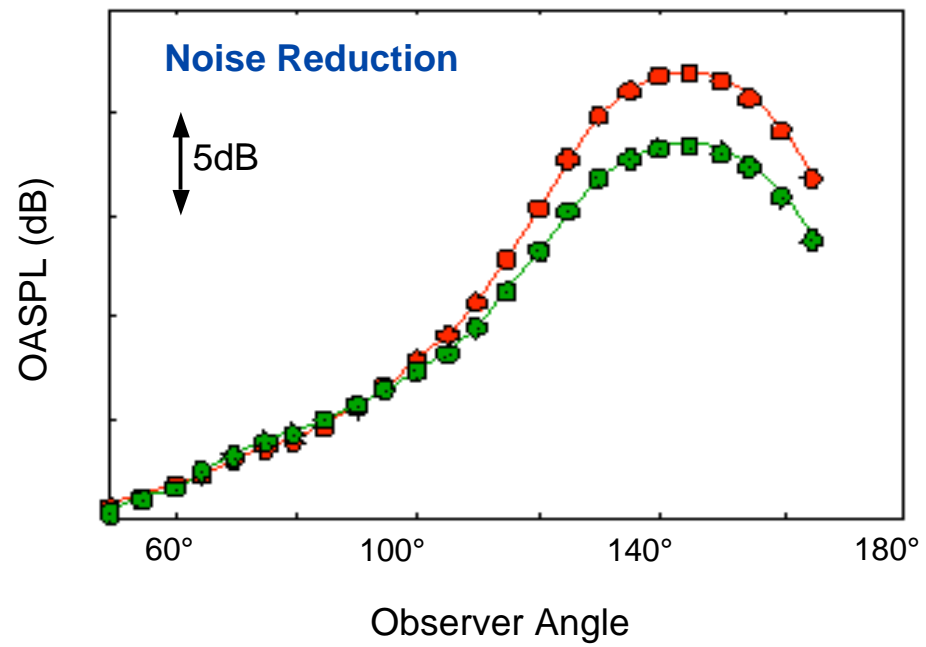
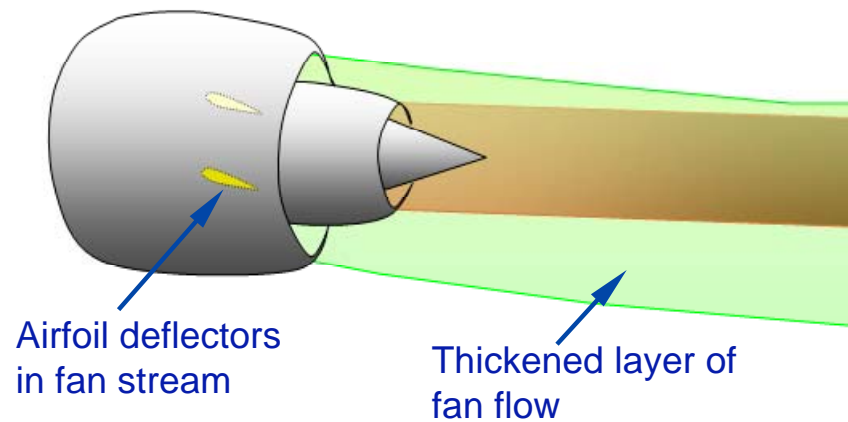


Air Injection for Broadband Shock Noise Reduction



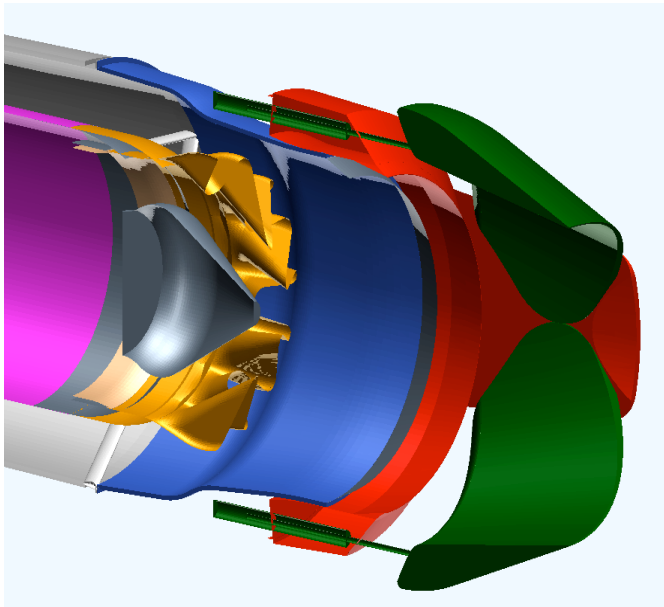


Supersonic Jet Noise Reduction via Reshaping the Exhaust Plume

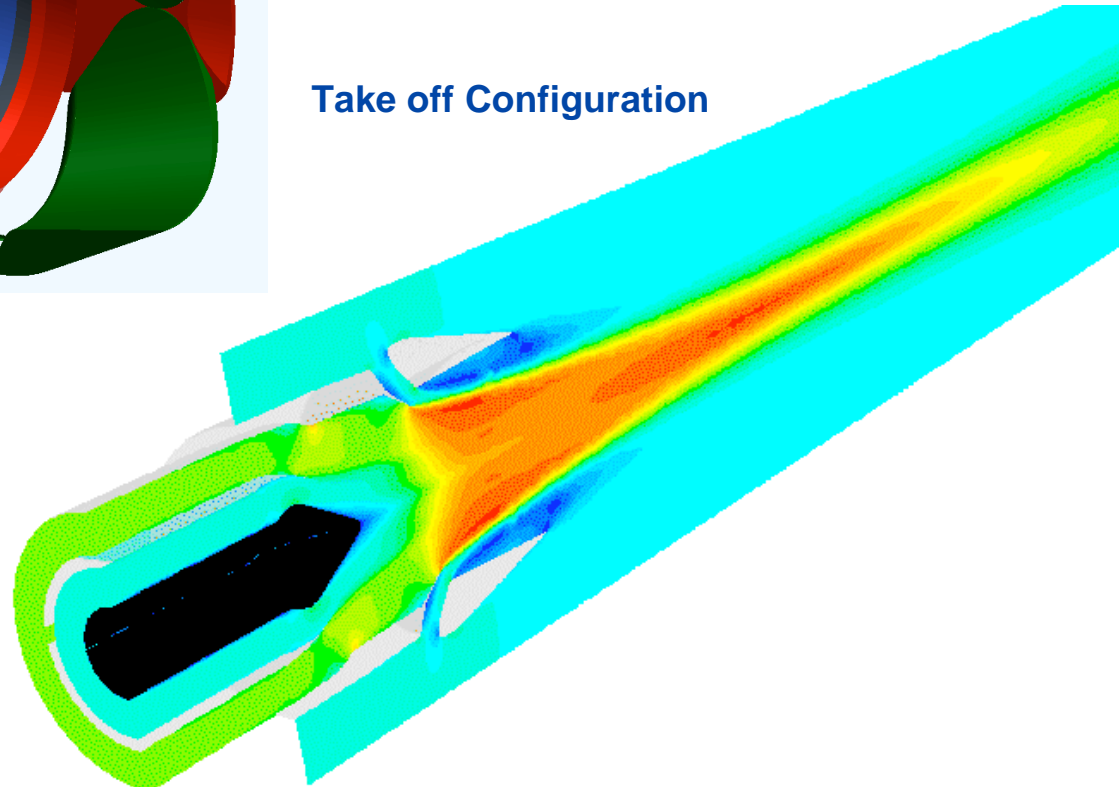
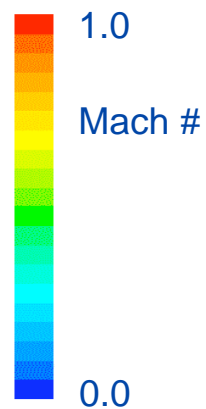




Variable Cycle Exhaust System Design for Supersonic Aircraft

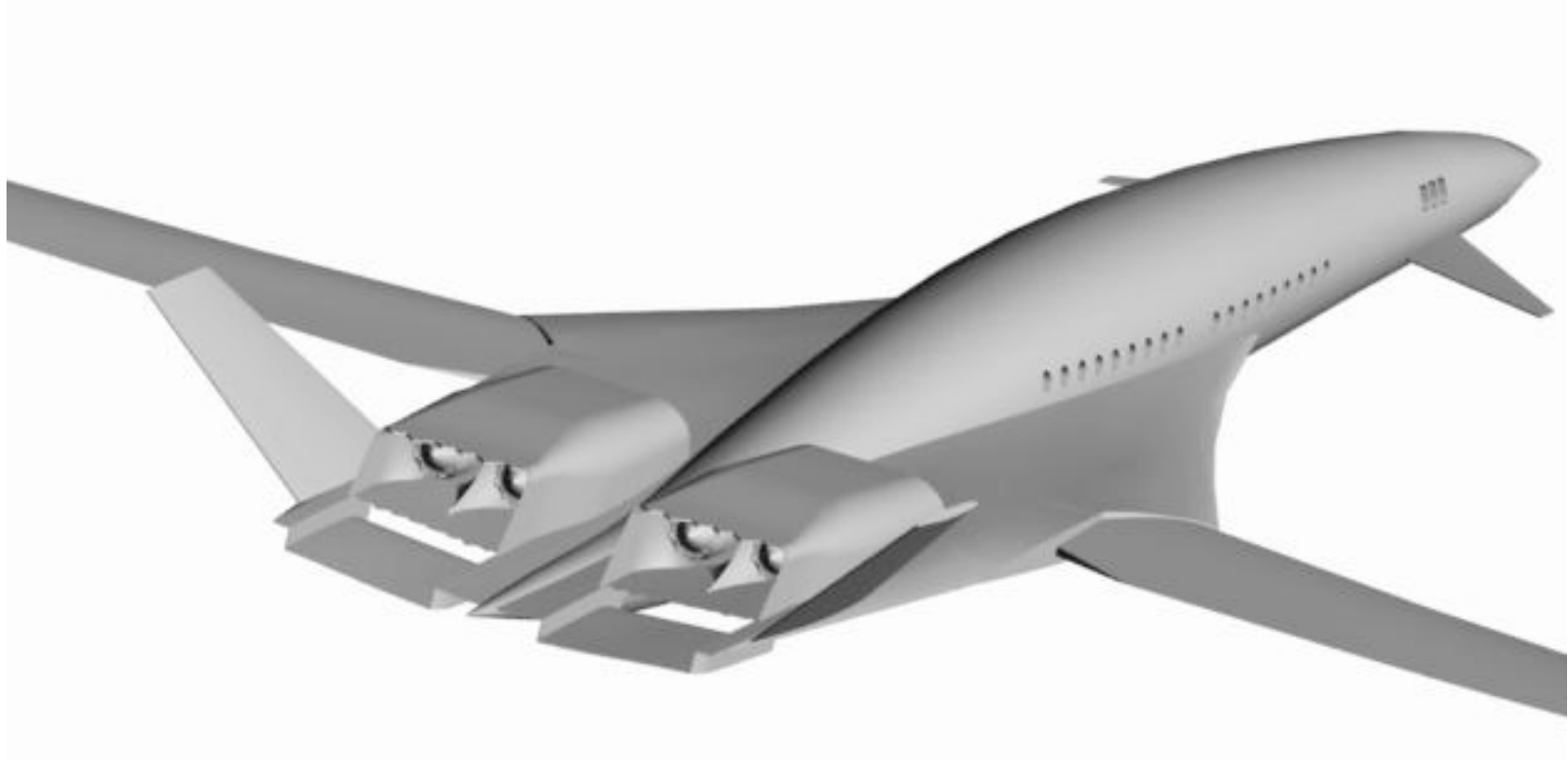


Take off Configuration





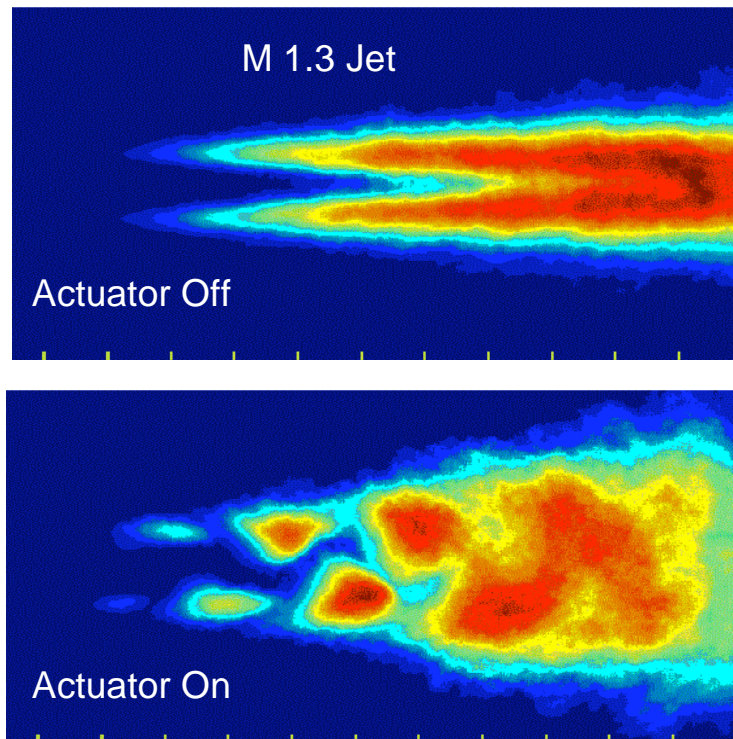
Iconic Supersonic Vehicle Exhaust System Design



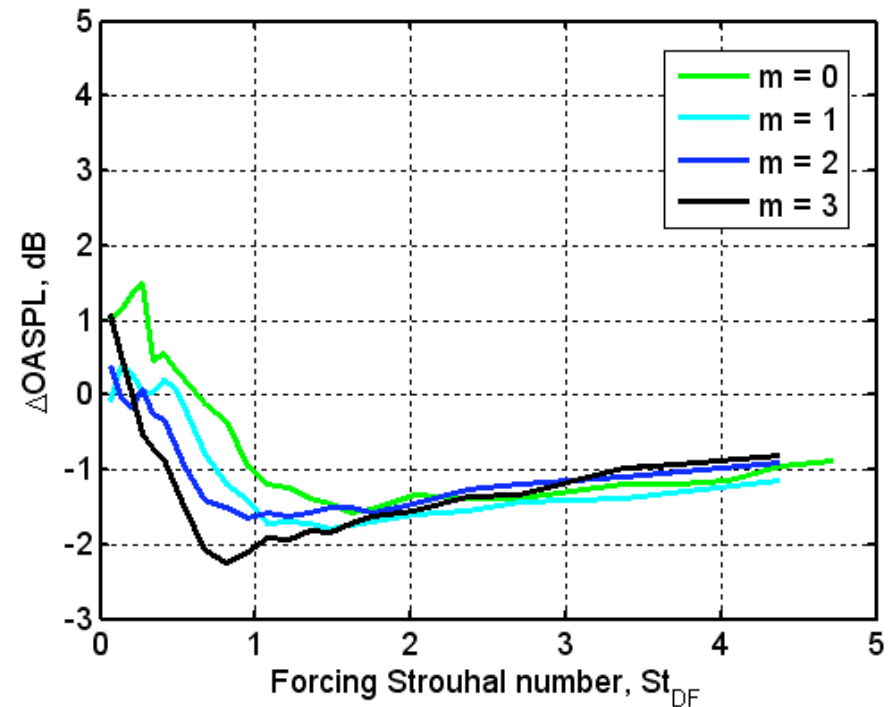


Supersonic Jet Noise Suppression Using Plasma Actuators

Flow Impact



Noise Reduction



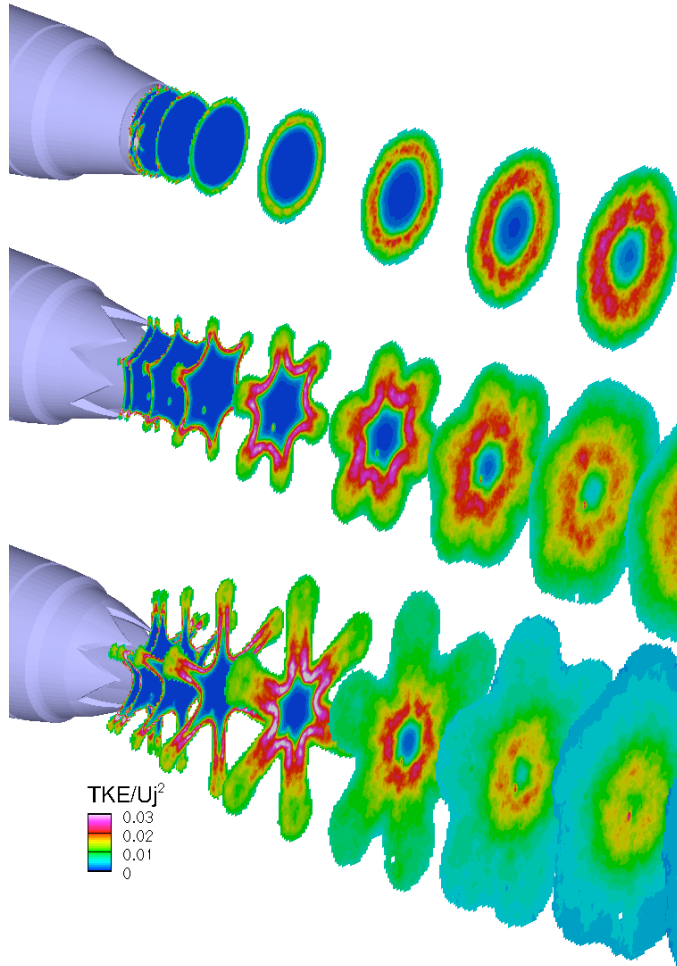


Airport Noise Elements

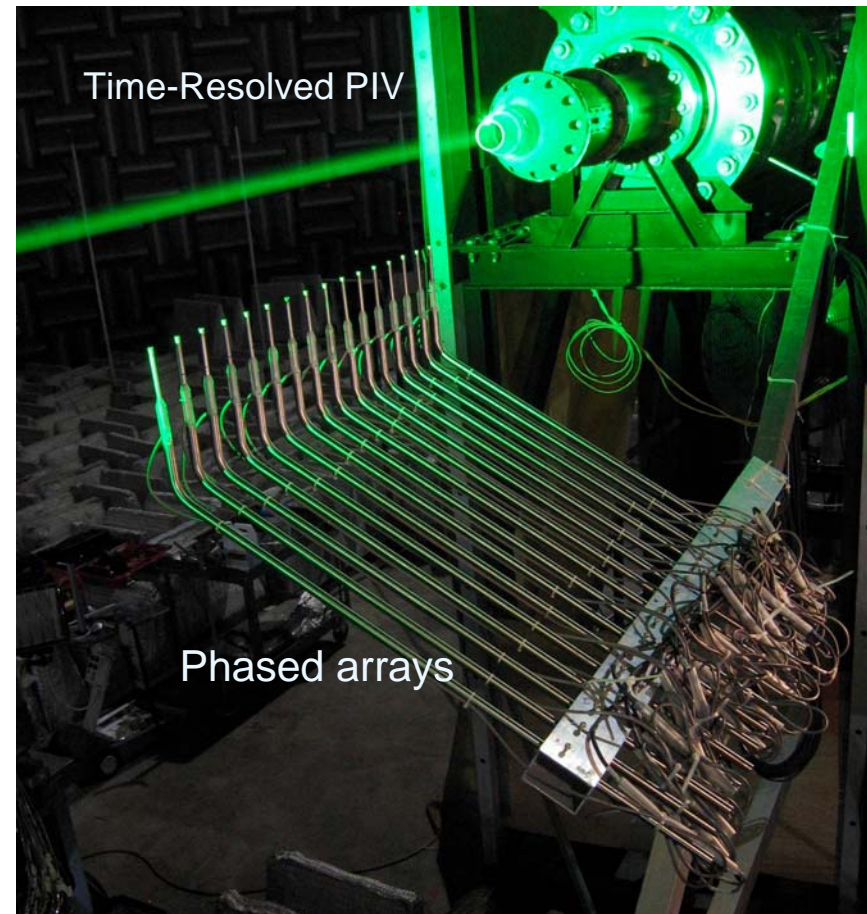
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Advances in Flow Diagnostics for Noise Reduction and Prediction

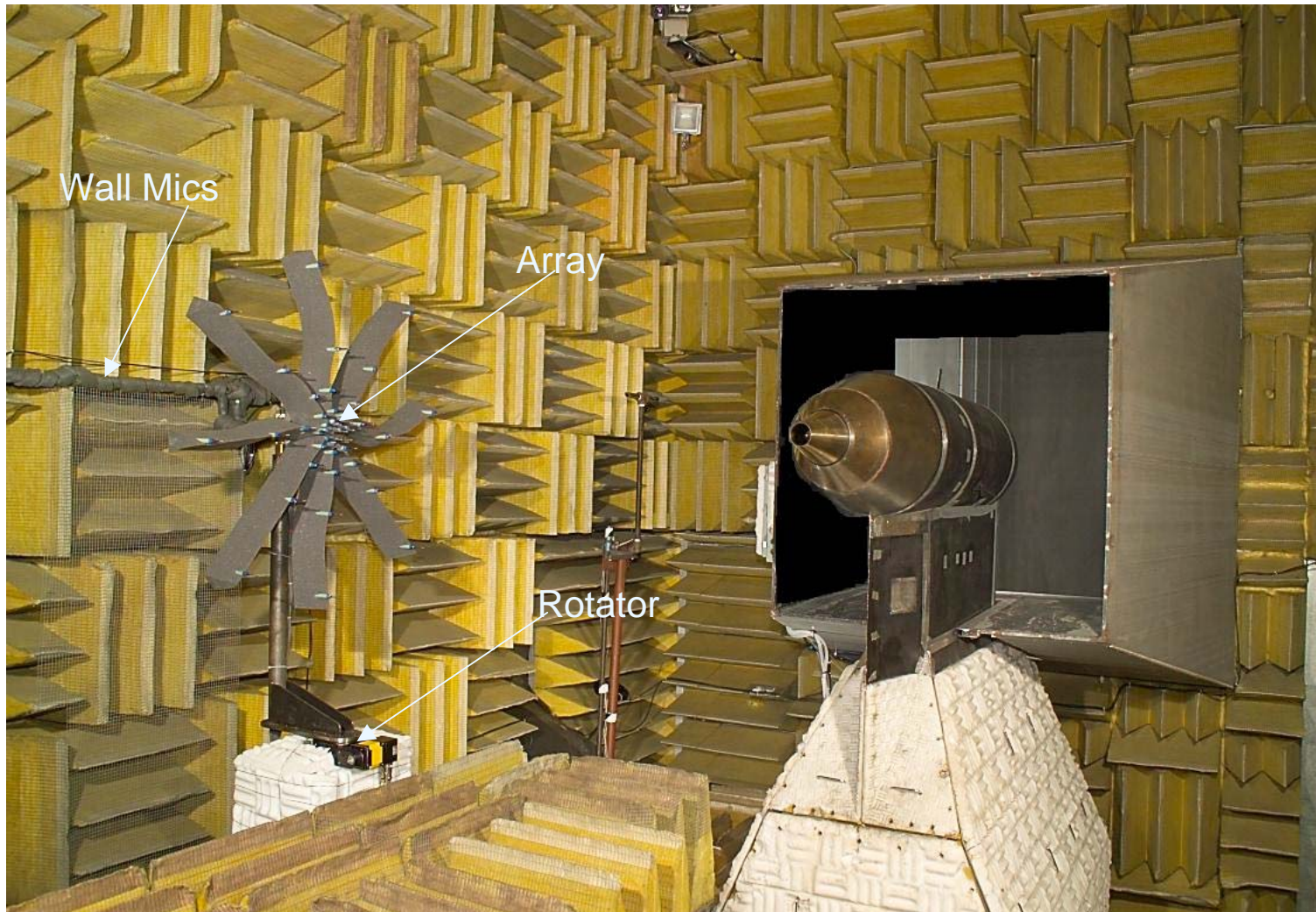
Turbulence measured in hot jets using Particle Image Velocimetry (PIV)



Flow-Source correlations explored using multiple advanced techniques



JEDA Measurements for Jet Noise

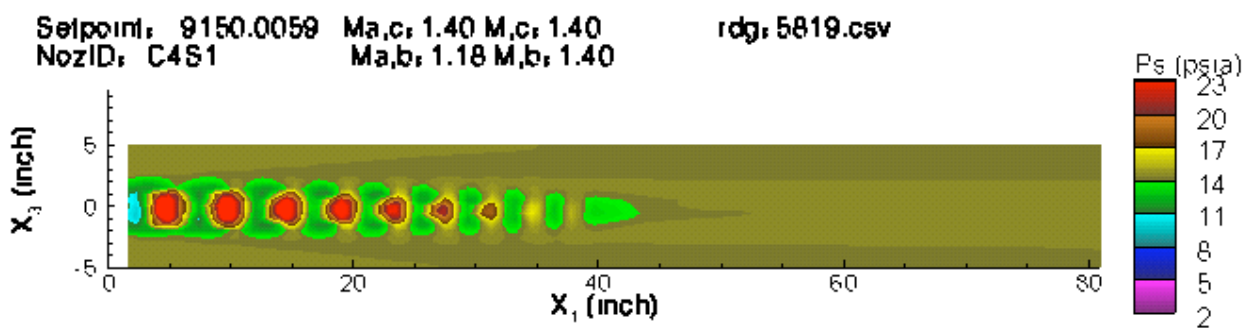
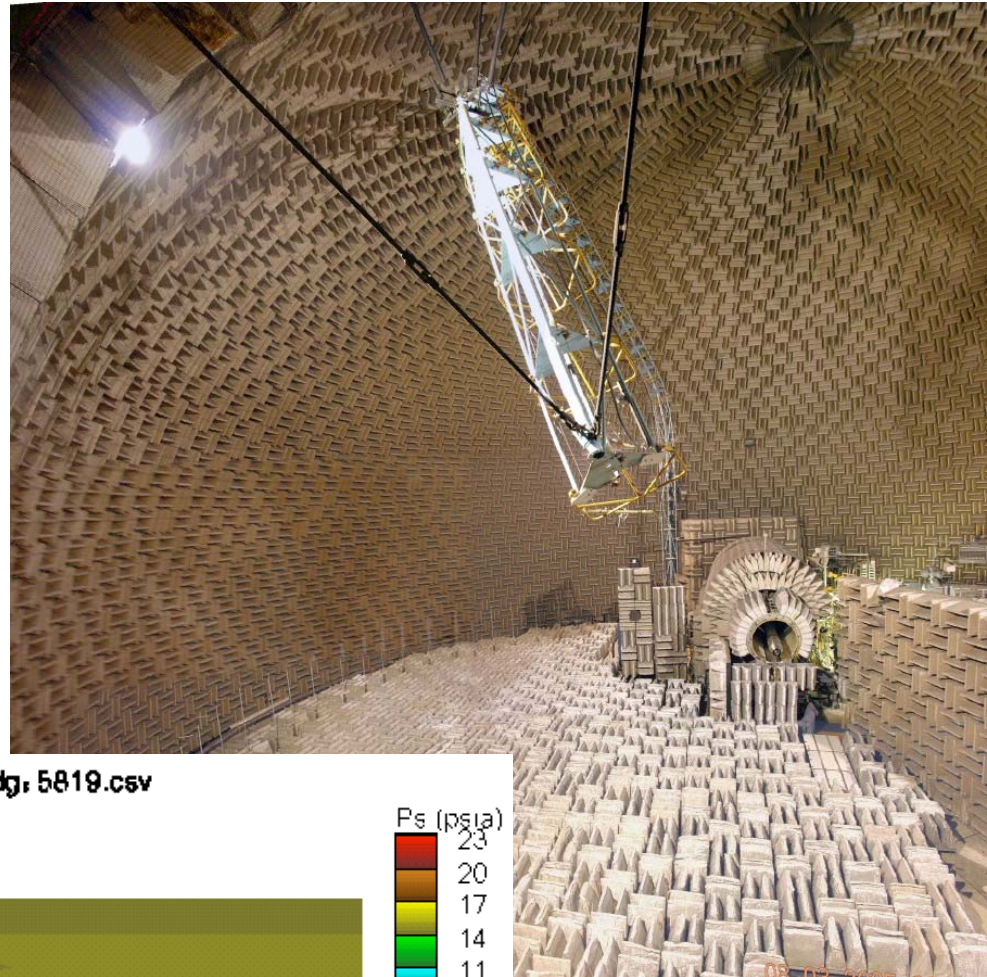


Array Installation in LaRC Jet Noise Lab



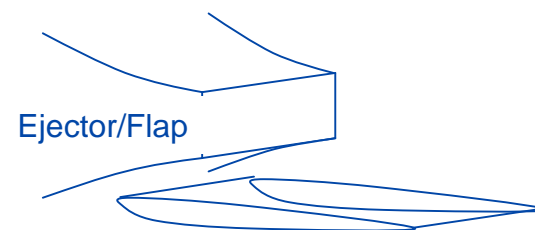
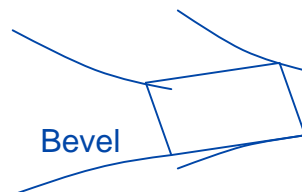
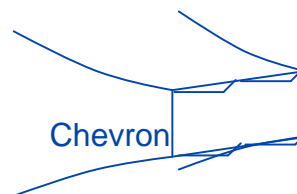
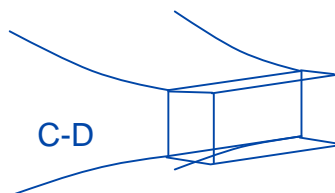
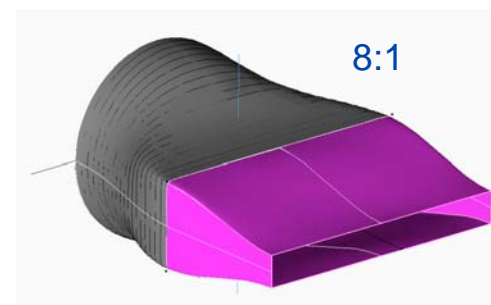
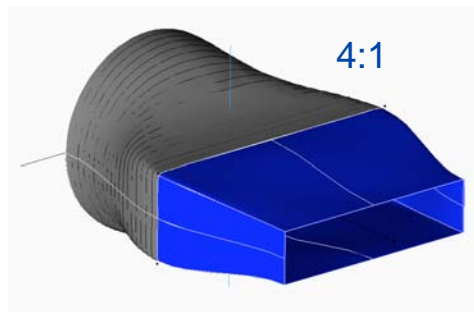
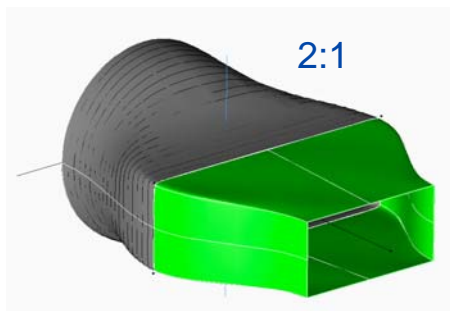
Supersonic Aeroacoustic Database

- Aero:
 - Pressure
 - Temperature
 - Turbulence
- Acoustic:
 - Far-field spectral directivity



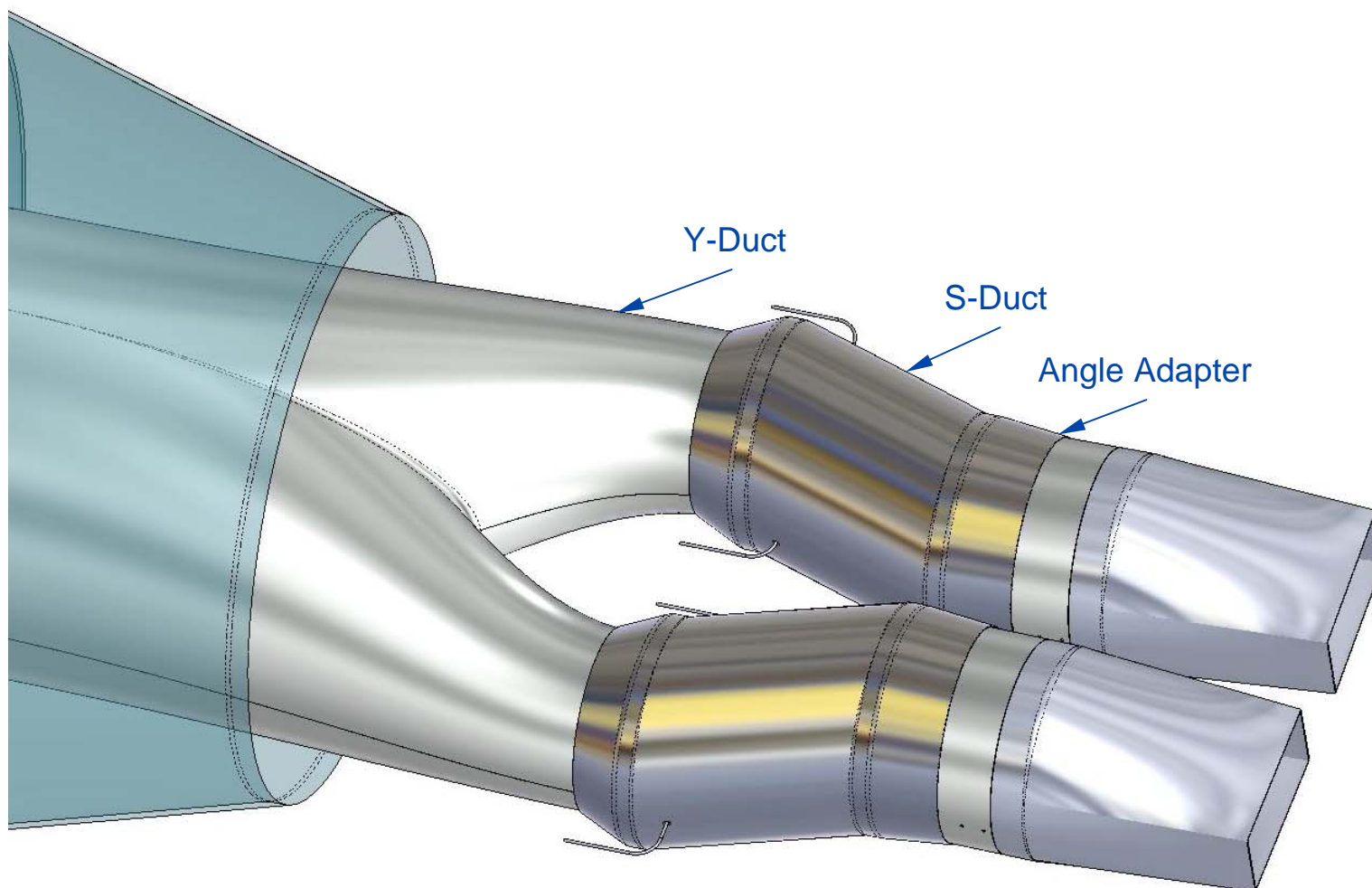


3D Jet Aeroacoustic Database





Twin Jet Aeroacoustic Database





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Motivation: Predict the Noise Impact of Each Concept and Explain

Baseline



Alternating Chevrons



Offset Bypass





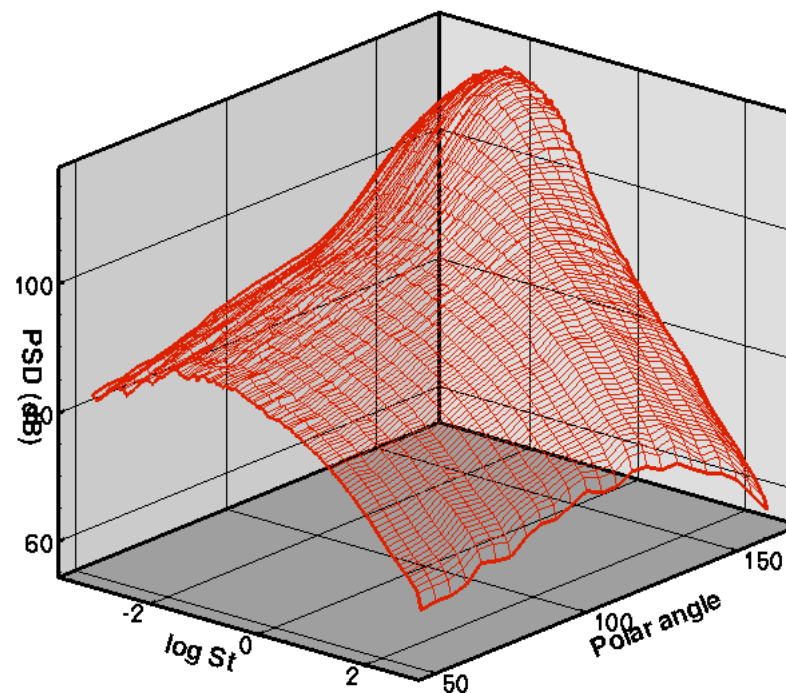
Scope of Prediction Methods

- Empirical Codes
 - ANOPP (ST2JET module)
 - Power Law (U^n modeling)
- RANS-based (Reynolds-Averaged Navier-Stokes) Codes
 - CFD
 - JeNo
 - Goldstein-Leib
 - BroadBand Shock-Associated Noise
- Time-Resolved Codes
 - LES
 - CAA



Jet Noise Spectral Directivity

Predict this shape over all speeds, temperatures, nozzle shapes...





Empirical Methods

- Stone's ST2JET
 - Part of ANOPP (total aircraft noise prediction code)
 - Extensive evaluation in 2007
 - Robust over enormous range of axisymmetric flow conditions
 - Average error in OASPL ~1-2dB
 - Very limited ability to predict 3D jets, installation effects
- Power Law (U^n) Model
 - Extends work of Viswanathan (2007)
 - Very good prediction of single flow jets
 - Useful for characterizing jet mixing noise in supersonic jets

$$OA(\phi, M_a, T_{tr}) = M_a^{N(\phi, T_{tr})} + B(\phi, T_{tr})$$

$$PSD(St, \phi, M_a, T_{tr}) = \widehat{PSD}(St, \phi) OA(\phi, M_a, T_{tr})$$



ANOPP Result

- Typical result for subsonic jet
 - Peak too low angle
 - Underpredicts peak noise level
 - Underpredicts high frequencies at peak angle

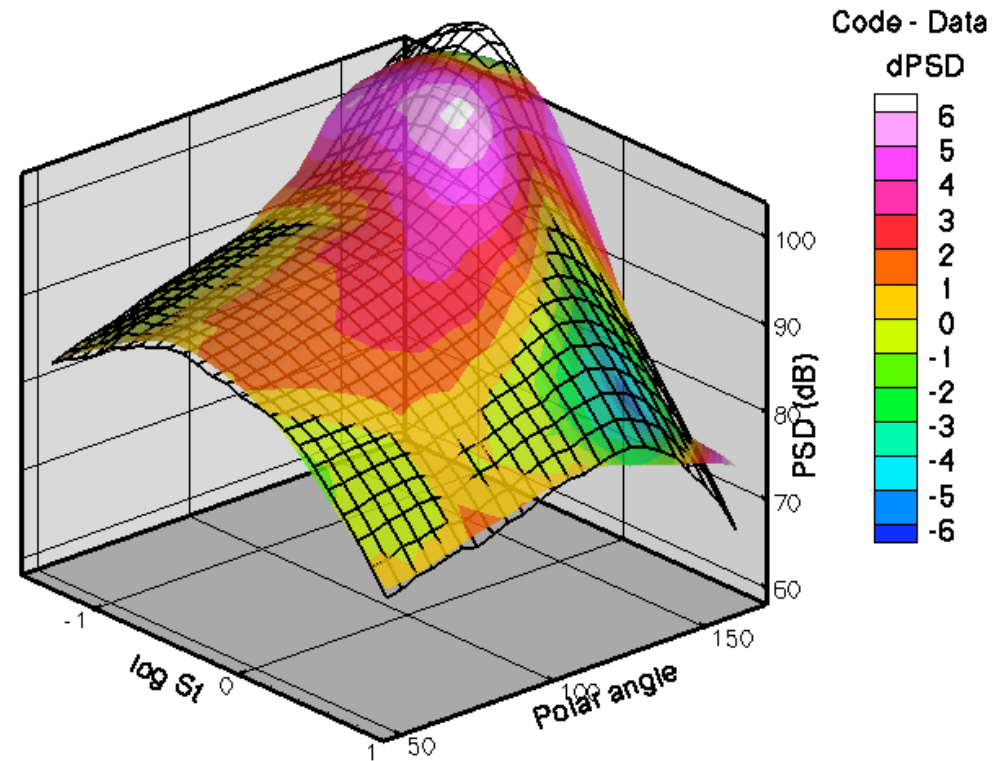
Key:

Shape is Power Spectral Density

- Black mesh = Data

- Color surface = Prediction

Color shows Prediction Error

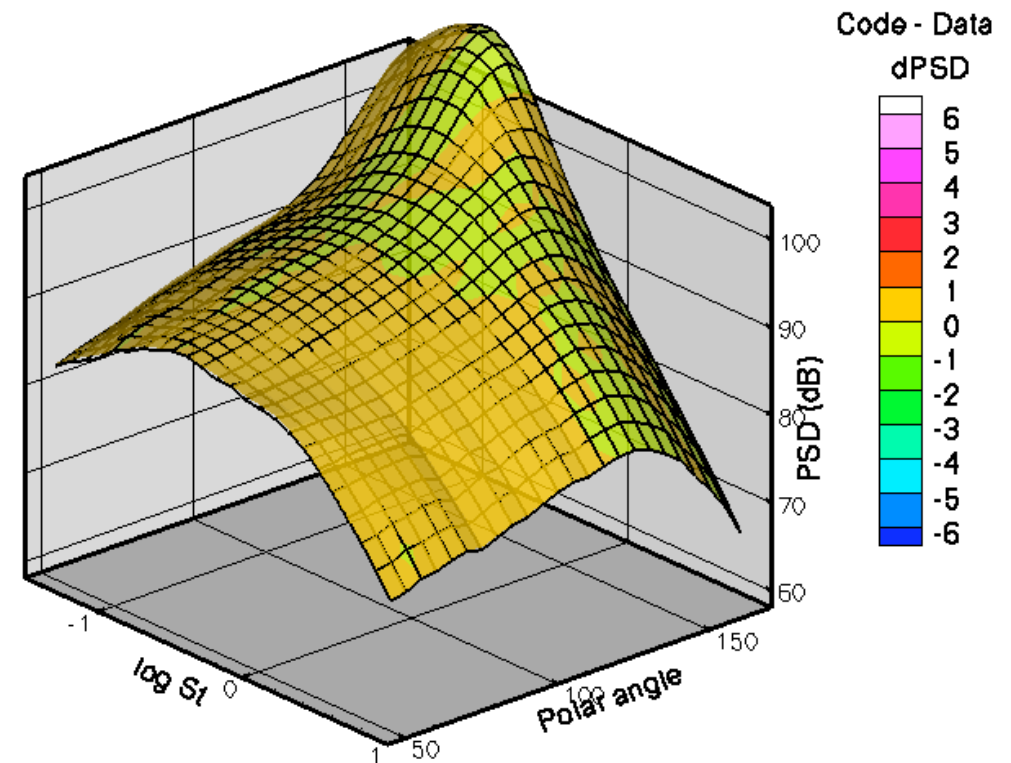


Ma=0.9, Ttr=1.0



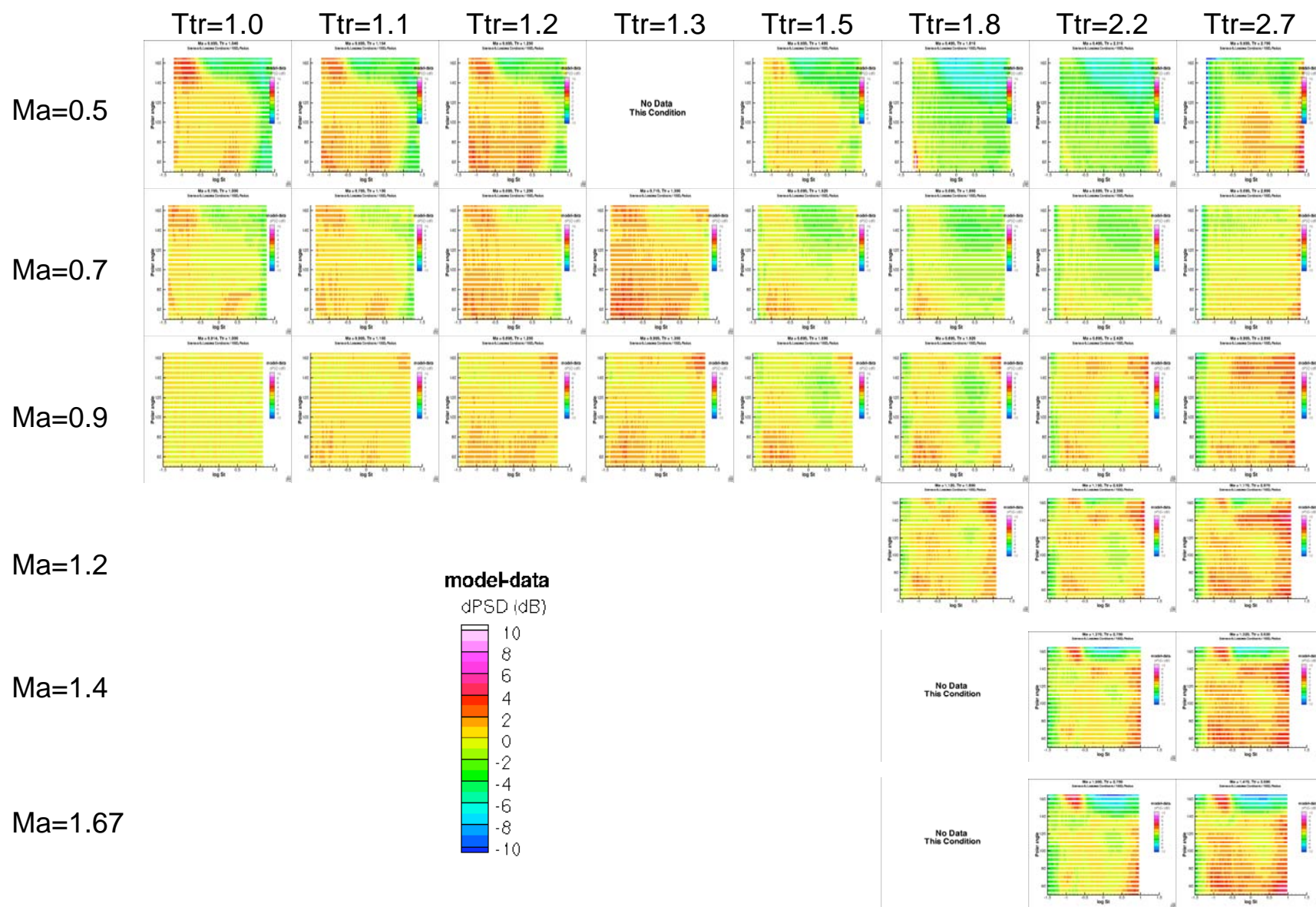
U^n Power Law Result

- Prediction fits this case very well
- What about others?
 - Plot dPSD for broad range of jet speeds (Ma) and temperature ratios (TtR)...



Ma=0.9, Ttr=1.0

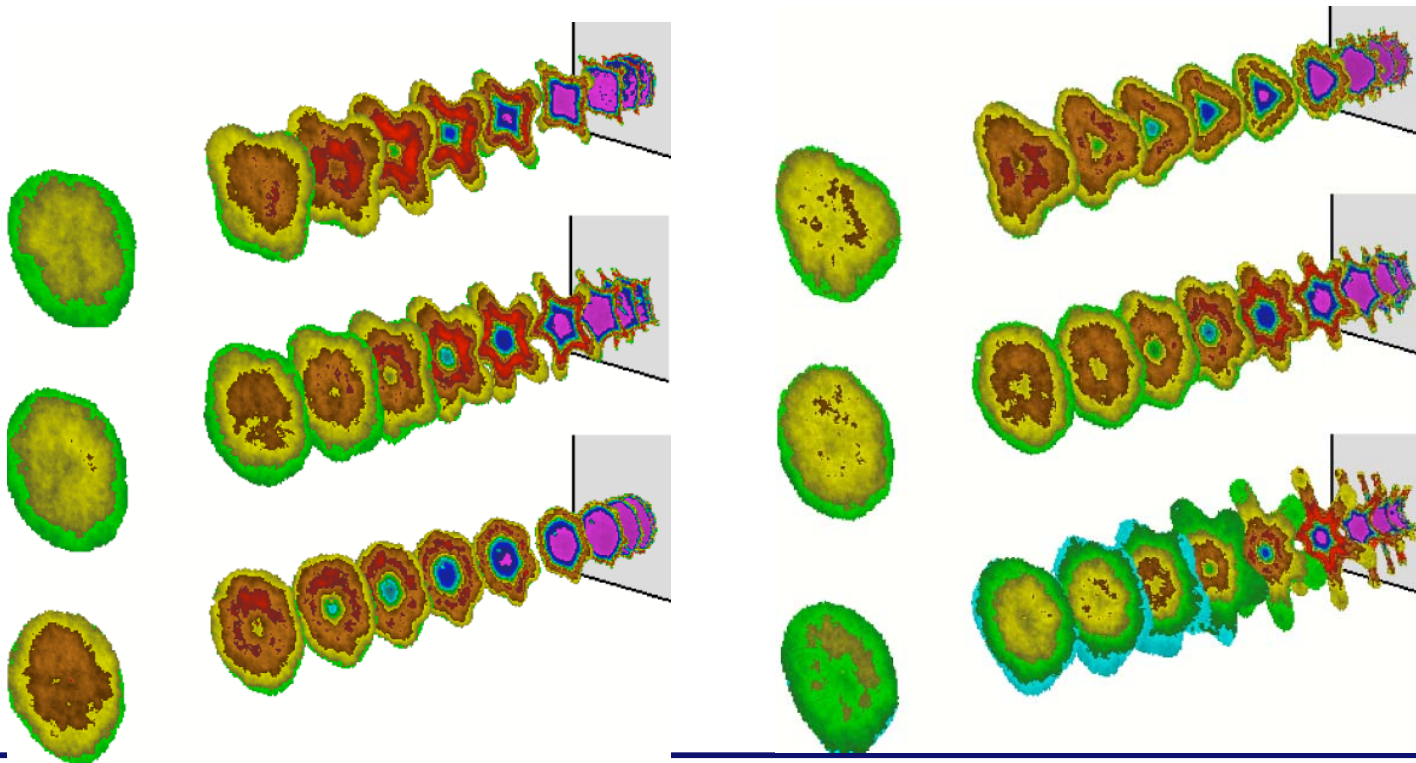
Un Global Fit—Subsonic Hot Jets





Geometric Parameters in Empirical Codes

- Empirical codes require experimental datasets with geometric features.
 - Cost, time, and accuracy to produce datasets
- Idea:
 - Use Modern Design of Experiments (MDOE) to quickly create geometry-dependent ANOPP jet noise modules
 - RANS-based prediction codes fill datasets





RANS-Based Methods

- Acoustic Analogy Theory
 - Navier-Stokes \Rightarrow 'Source + Propagation' form
 - Assumptions and models required to solve
- Sources:
 - Correlations of Reynolds stress and of velocity-enthalpy.
 - Turbulent Kinetic Energy, Turbulent Enthalpy, and Dissipation from RANS CFD
- Propagation:
 - Coupling with, distortion through inhomogeneous mean flow.
 - Green's function method with approximations
- Major common assumptions
 - Compact source (coherence length \ll wavelength)
 - Locally parallel flow
 - Axisymmetric propagation
 - Simple turbulence model for space-time correlations



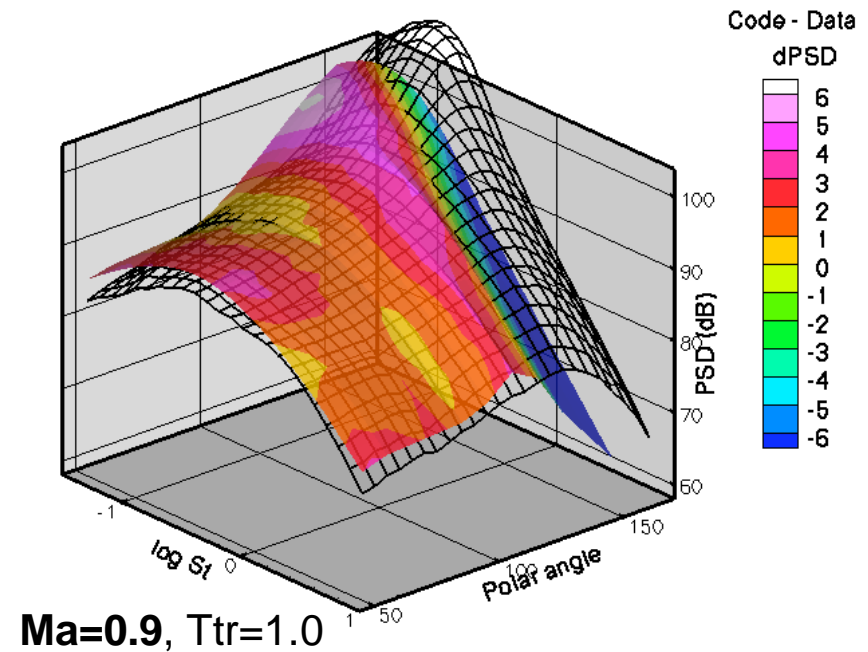
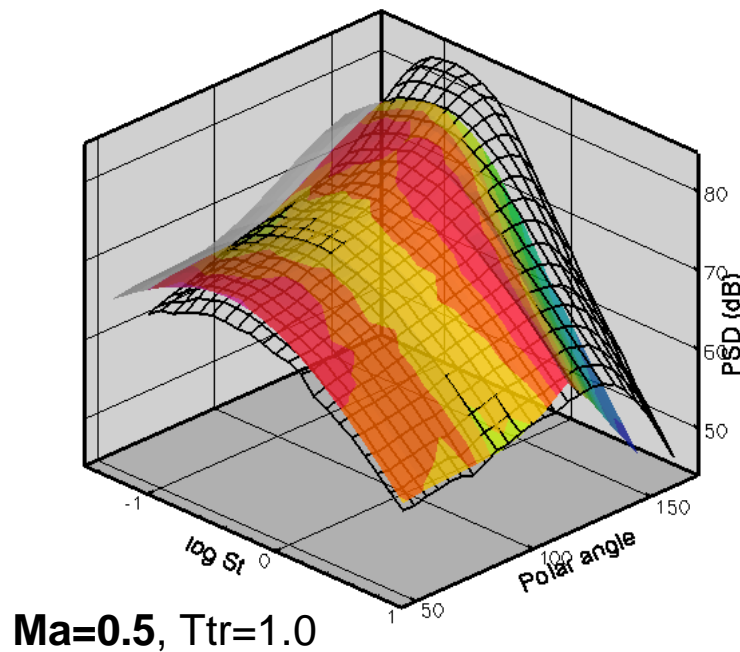
Acoustic Analogy Code Status

- JeNo v1—Jet Mixing Noise
 - No Turbulent Enthalpy* source—misses hot jets
 - No broadband shock source*—misses shocked jets
 - Uses parallel flow assumption
 - Uses source noncompactness model with simple isotropic turbulence
- Goldstein-Leib—Jet Mixing Noise
 - No Turbulent Enthalpy source—misses hot jets
 - No broadband shock source—misses shocked jets
 - Uses weakly nonparallel flow assumption
 - Uses source noncompactness model with axisymmetric turbulence
- Penn State BBSAN—Broadband Shock-Associated Noise
 - Models sound of turbulence-shock interaction only



JeNo v1 for Cold Subsonic Jets

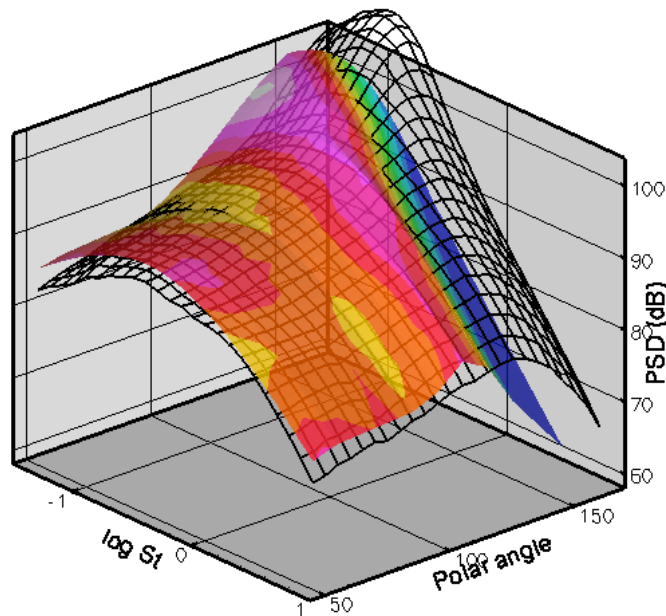
- JeNo v1 predicts spectral shape at broadside angles through 120° within 2dB
- Predictions roll off too quickly at aft angles $> 150^\circ$
 - Gets worse at higher speed
 - Zone of silence starts too far upstream



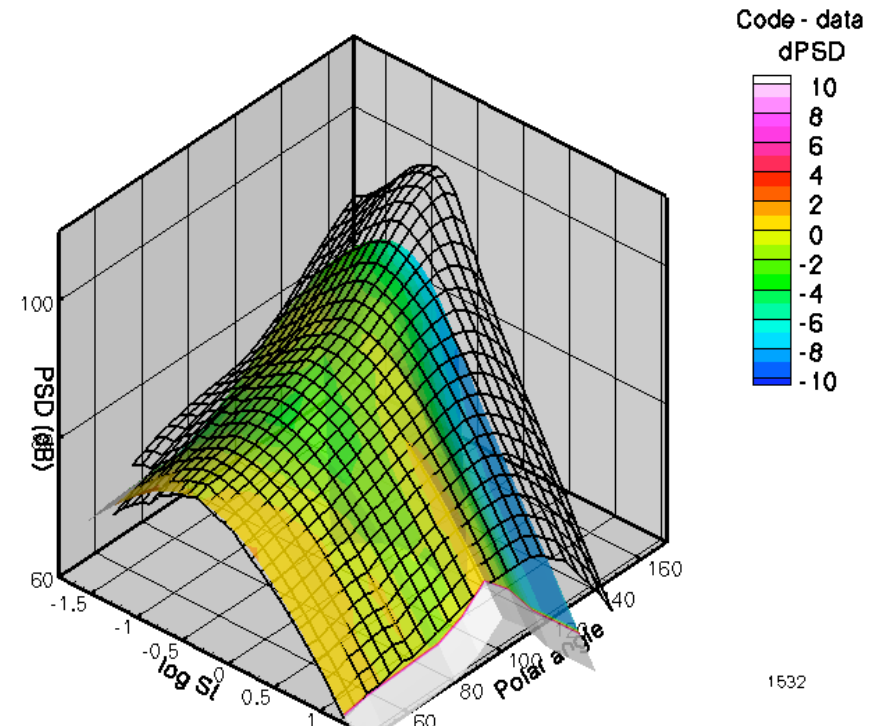


JeNo v1 for Hot Subsonic Jets

- Underpredicts jet noise at all angles, frequencies
- Typical of jet noise codes that ignore enthalpy source



Ma=0.9, Ttr=1.0

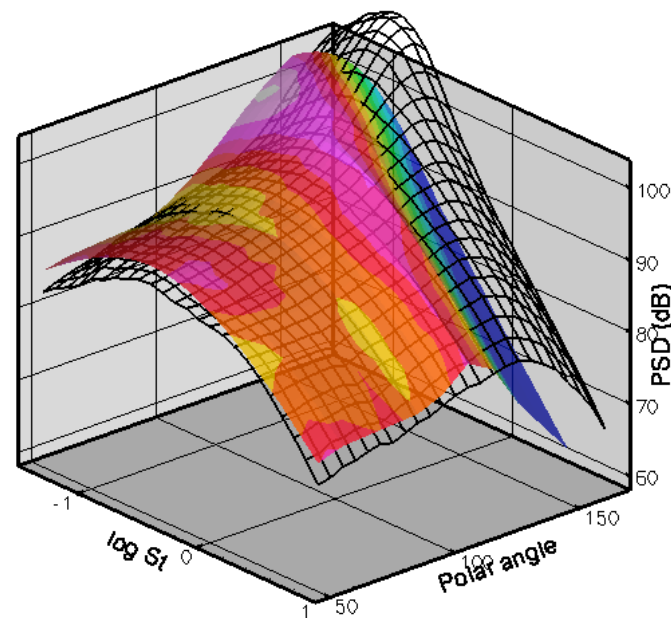


Ma=0.9, Ttr=1.6

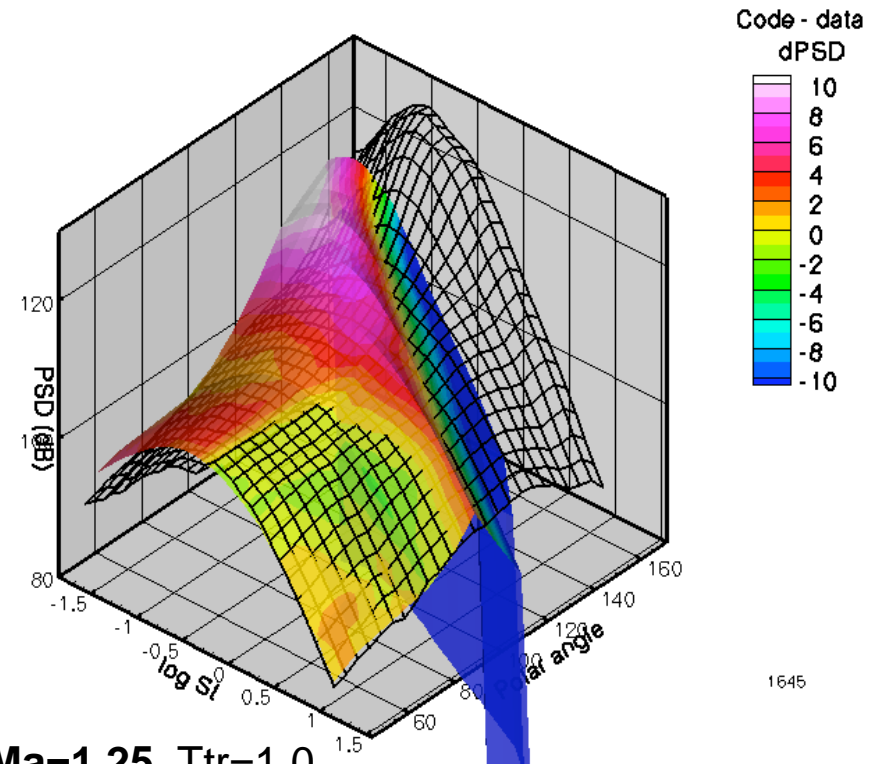


JeNo v1 for Cold Supersonic Jets

- Trend of mis-predicting 'zone of silence' continues as speed increases



Ma=0.9, Ttr=1.0

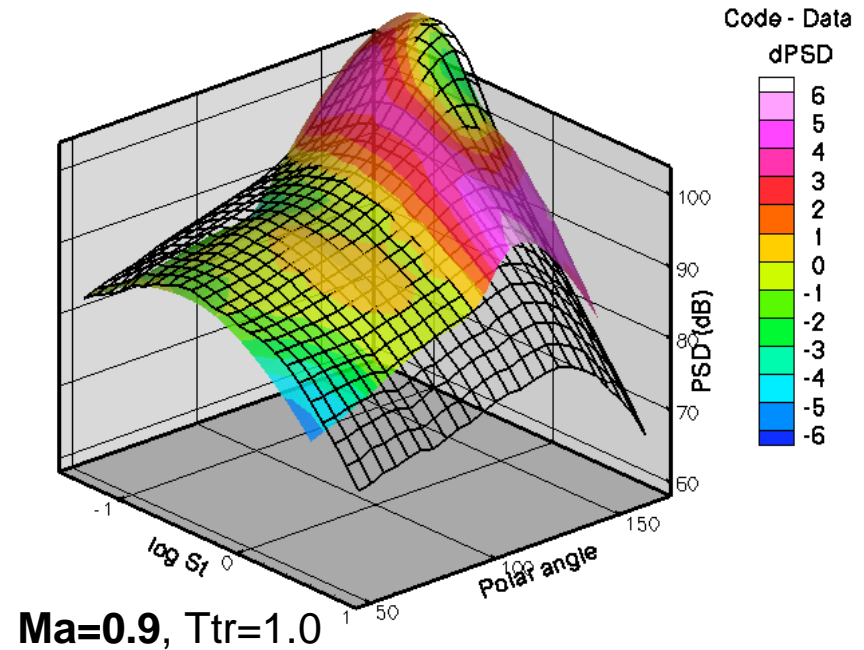
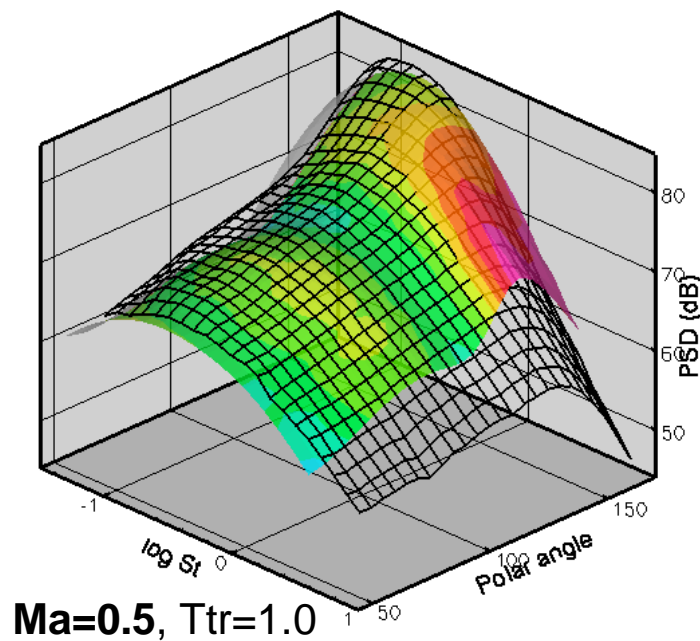


Ma=1.25, Ttr=1.0



Goldstein-Leib For Cold Subsonic Jets

- Much better agreement with data at aft angles
 - Nonparallel flow assumption and advanced turbulent source model
- Has proper trend with increased speed





Complex Geometries in RANS-based Codes

- RANS CFD gives impact of geometry on flow
- Assumptions about geometry of shear layers limited to Green's solution for propagation
- Captures noise trends with geometric variations

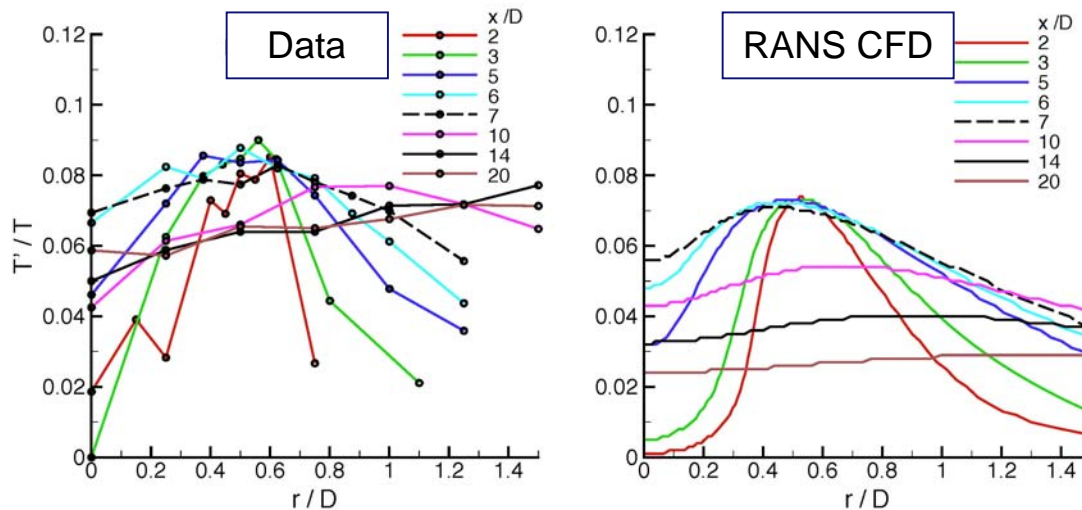




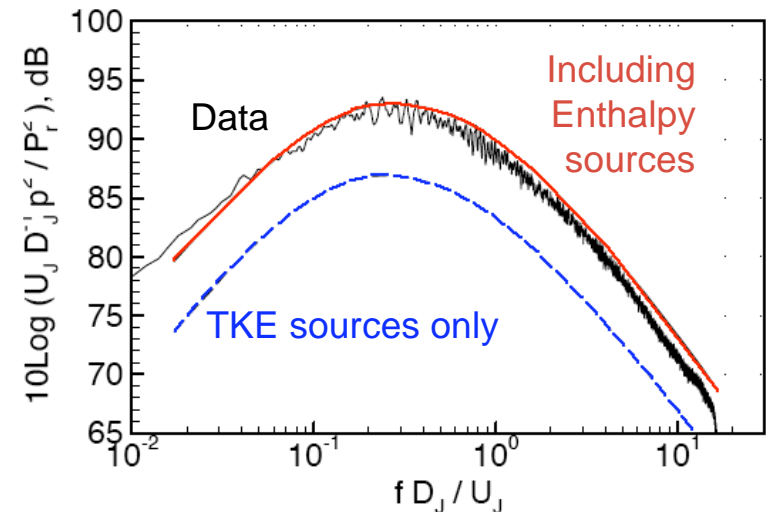
Development Status—Enthalpy Source

- Turbulent Enthalpy equations being coded into Wind RANS CFD code
- Calibrated/validated by measurements of turbulent temperature using Rayleigh and Raman techniques.
- Preliminary results show good modeling of turbulent temperature
- Provides the missing source strength for hot jets

Radial Profiles of Temperature RMS
Rayleigh Scattering Data vs RANS CFD (CRAFT Inc)

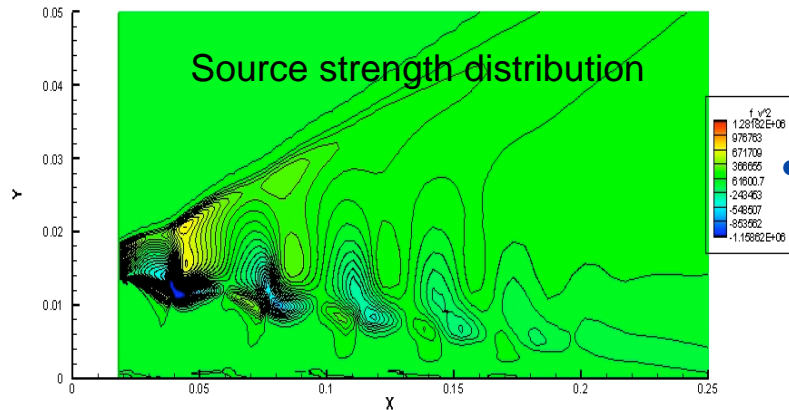


Improvement in Jet Noise Prediction
with Hot Source Included

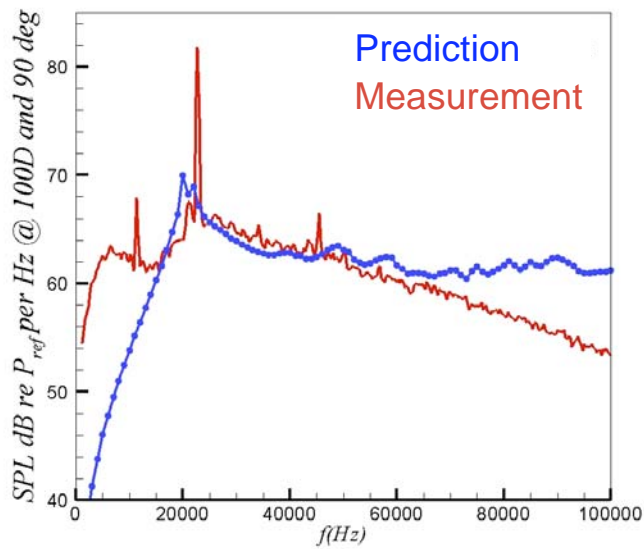




Development Status—Broadband Shock Noise



- Model for Broadband Shock Noise being developed under NRA by Prof Philip Morris, PSU
- Noise model based on RANS CFD prediction for shock cell structure and on model for two-point turbulence statistics
 - Captures observed trends
 - Requires ~1 hour per observer angle to compute (before optimization)
 - Reviewing details of turbulence source statistics to improve high frequency predictions





Time-Resolved Methods

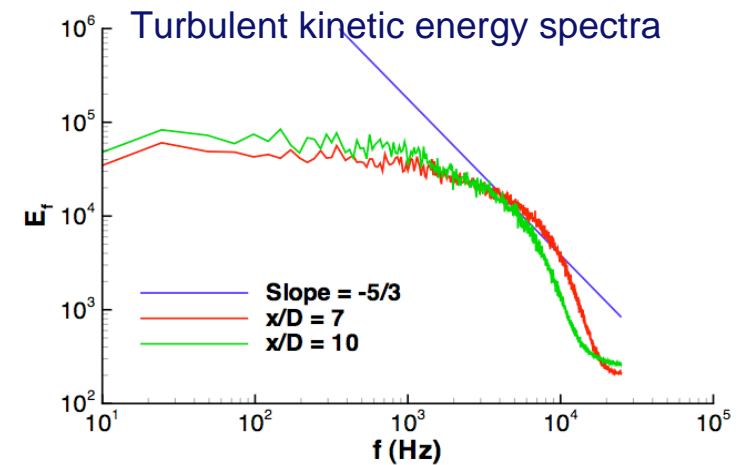
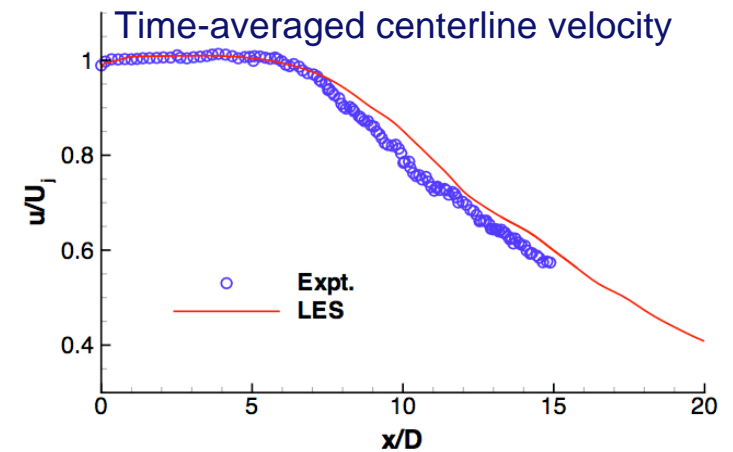
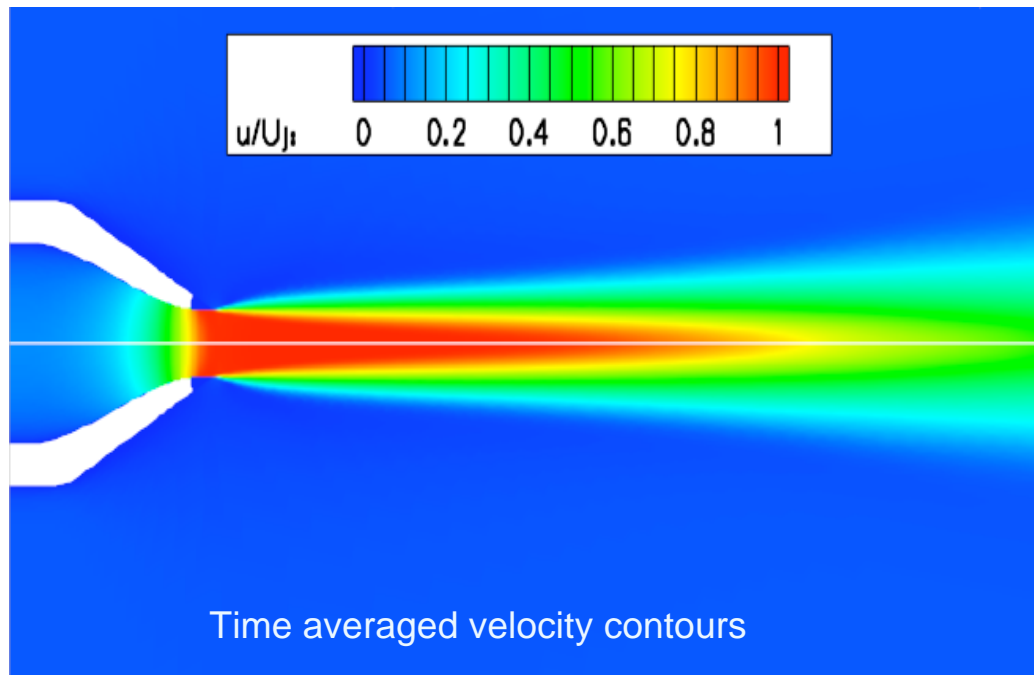
- Large-Eddy Simulations
 - Best practices
 - Validation for jets (beyond mean flow)
 - Application to 3D geometries, jet forcing
- Exact CAA solutions
 - Validate 3D Green's function approximations



NASA Large-Eddy Simulation Research

- In-house research code for LES method evaluation
- Have tried and discarded many reportedly good ideas

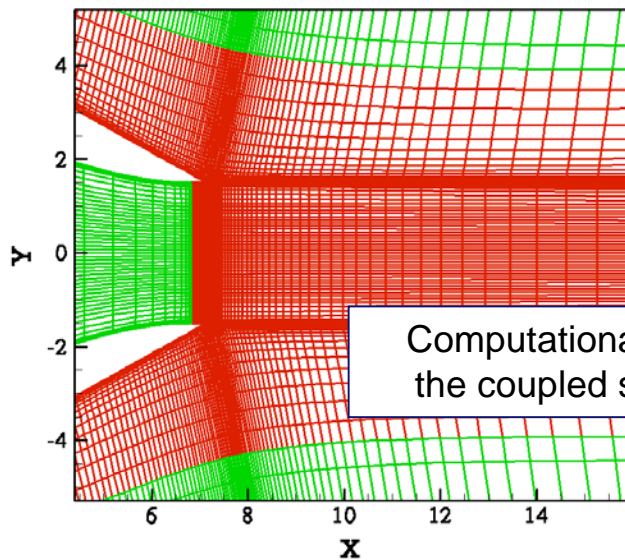
Mach 0.9 round jet using Bogey & Bailey
13 pt. DRP scheme



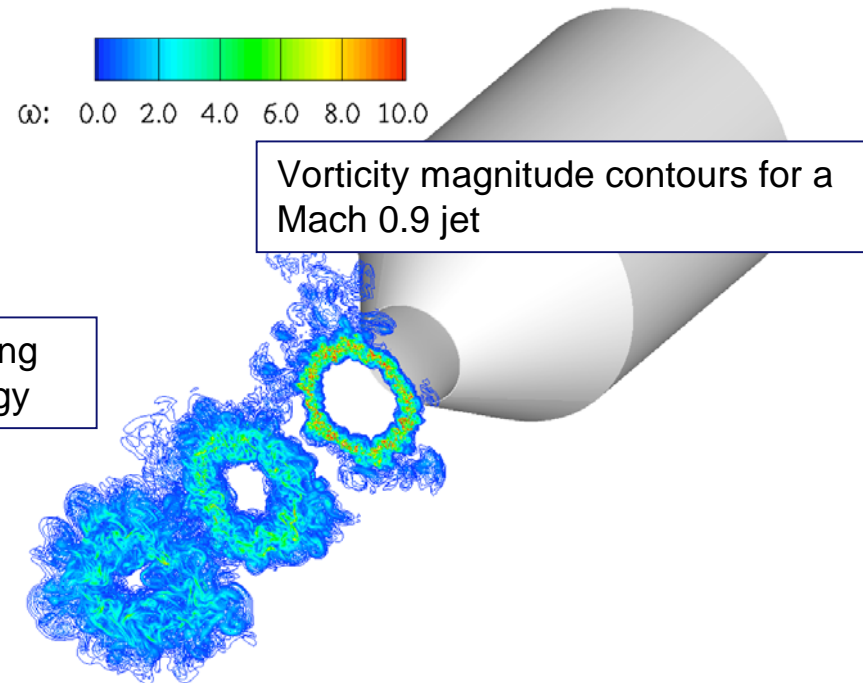


LES for Nozzles of Complicated Geometry

- LES of noise suppressing nozzles with complex geometry by Sanjiva Lele, Stanford University.
- Developing computational tools to coupled Reynolds Averaged Navier-Stokes (RANS) and Large-Eddy Simulation (LES) methods for efficient jet noise analyses.



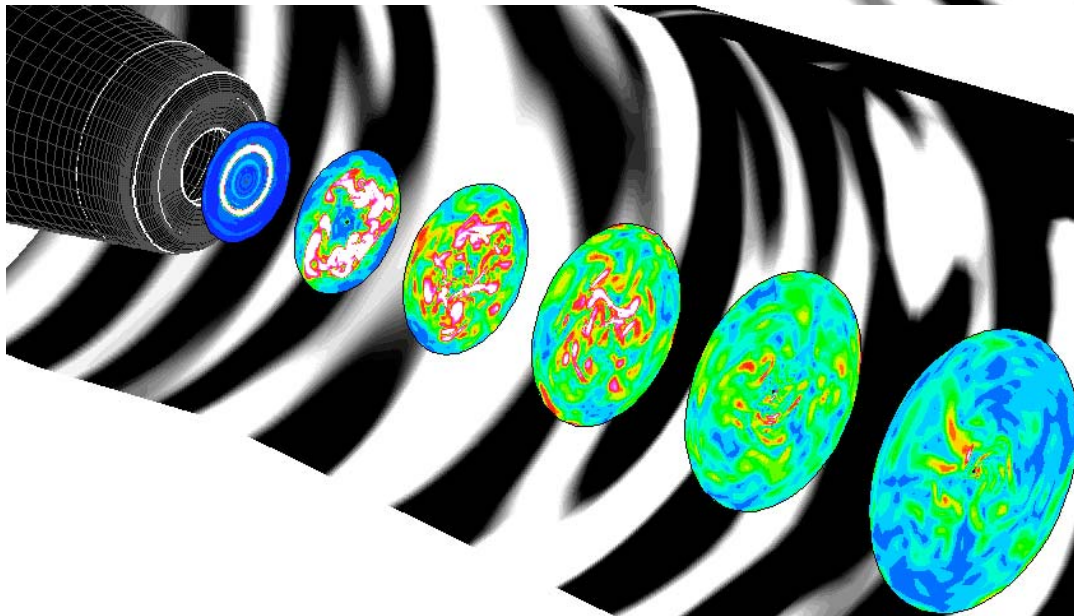
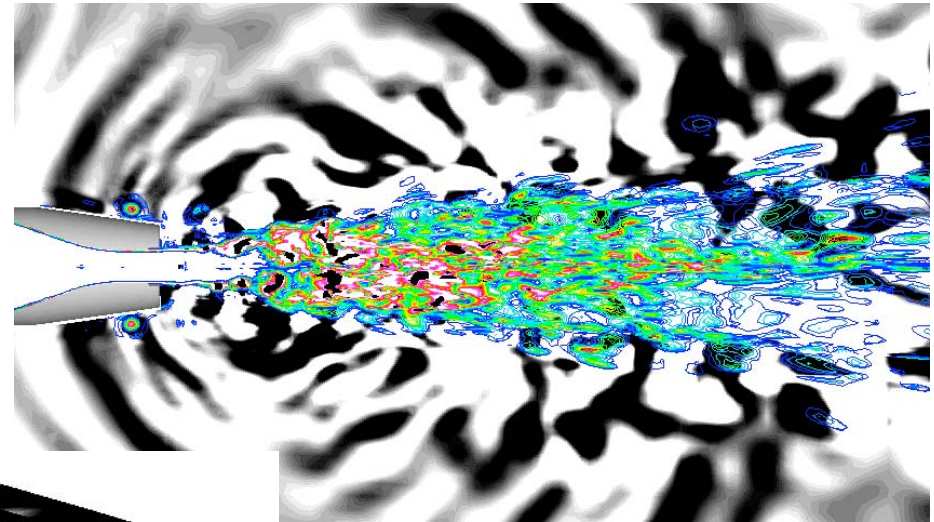
Green: URANS, NSSUS code
Red: LES, CDP-C code





LES for Jet Excitation

- LES being performed by Dan Bodonoy, UIUC to feed optimization algorithm for controlled minimization of jet noise.
- To be used in OSU plasma actuator study



M=1.3 ideally expanded jet
Vorticity magnitude and density
fluctuation



Summary

- Empirical methods ($\sim O(\text{seconds})$)
 - Robust for axisymmetric jets, cycle analysis
 - Cannot be applied to complex geometries without fresh input
- RANS-based methods ($\sim O(\text{hours})$)
 - Systemic errors identified, plans to address formulated
 - Development of accurate code for hot supersonic jets seems within reach
 - Delivers answers to detailed engineering design questions
 - Propagation in highly 3D and around solid bodies are next challenge
- Time-resolved methods ($\sim O(\text{months})$)
 - Best practices being codified
 - Moving toward research application: complex geometries, active control
- **Aeroacoustics will soon be on par with aerodynamics as an engineering science.**

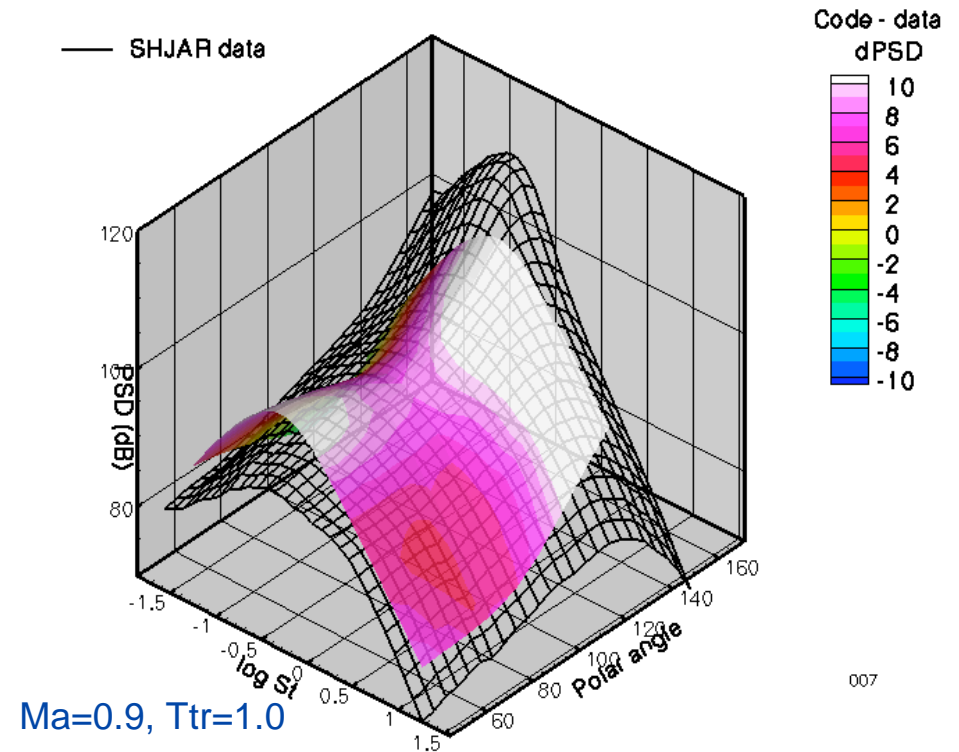
Backup Charts





Jet3D for Cold Subsonic Jets

- Jet3D overpredicts cold jet amplitudes by 8-10dB at broadside angles
- Does not predict change in peak frequency with increasing angle.





Supersonics Project Airport Noise Technical Challenge

James Bridges
API, Airport Noise
Fundamental Aeronautics Annual Meeting
Atlanta, GA
8 October 2008